ARL-TR-7473 ● SEP 2015

US Army Research Laboratory

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NOTICES

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Sensors and Electron Devices Directorate, ARL

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* Sep 2015	**2. REPORT TYPE** Final
3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Bragg Reflector-Induced Increased Nonradiative Lifetime in Gallium Arsenide (GaAs)/Aluminum Gallium Arsenide (AlGaAs) Double Heterostructures	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Patrick A Folkes, Blair Connelly, Harry Hier, William Beck, and Brenda Van Mil	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Research Laboratory ATTN: RDRL-SED-E 2800 Powder Mill Road Adelphi, MD 20783-1138	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-7473
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A novel technique is used to determine the minority carrier lifetimes, interface recombination velocity, and radiative recombination constant from time-resolved photoluminescence measurements on a set of 3 molecular beam epitaxy (MBE)-grown gallium arsenide (GaAs)/aluminum gallium arsenide (AlGaAs) double heterostructures (DHs) and published theory. This technique is used to determine that a distributed Bragg reflector between the substrate and the DHs increases the GaAs nonradiative lifetime. The fractional increase in the nonradiative lifetime varies with the MBE growth parameters.

15. SUBJECT TERMS
Semiconductor

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Patrick A Folkes
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER (Include area code)**
Unclassified	Unclassified	Unclassified	UU	16	301-394-1042

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

Knowledge of the semiconductor nonradiative lifetime is essential for the design and analysis of high-efficiency semiconductor solar cells[1] and other optoelectronic devices.[2] Time-resolved photoluminescence (TRPL) measurements at 300 K were used to determine the radiative lifetime of the gallium arsenide (GaAs)/aluminum gallium arsenide (AlGaAs) double heterostructures (DHs) from the photoluminescence (PL) decay time, which is the effective minority carrier lifetime. PL decay time measurements, which are typically used for the determination of the minority carrier lifetime in GaAs, are sensitive to surface recombination,[3,4] recombination at the active layer/substrate interface,[5] and self-absorption of recombination radiation.[6,7] Due to the large surface recombination velocity (10^5 – 10^6 cm/s) at the free GaAs interface[4,8] and the substrate/active layer interface[5], measurements of the PL decay time can be dominated by these effects depending on the carrier density, the sample thickness and the bulk defect density in the GaAs sample. Consequently, the unambiguous determination of minority carrier lifetime and the radiative lifetime typically requires measurement over a range of sample thicknesses and carrier densities.

The surface and interface recombination velocity in GaAs was considerably reduced by the use of GaAs/AlGaAs DHs that confine minority carriers in the GaAs quantum well defined by the potential barrier at the GaAs/AlGaAs interface due to the larger bandgap in AlGaAs.[9] Theoretical analysis showed that self-absorption of spontaneously emitted photons has significant effects on the lifetime of injected carriers in GaAs/AlGaAs DHs.[7] Minority carrier lifetimes and the radiative recombination constant were determined from PL decay time and internal radiative quantum efficiency measurements on GaAs/AlGaAs DH samples and theory, which takes into account self-absorption and interface recombination.[10] One approach to a high-efficiency GaAs solar cell uses a GaAs/AlGaAs DH with a roughly 1–2 µm GaAs active region on top of an internal distributed Bragg reflector (BR) to take advantage of photon recycling effects. However, the effect of the growth of the BR on the deep level trap density of the GaAs active layer that determines the nonradiative lifetime has not been investigated. In this report, we detail the results of an experimental investigation of the effect of a BR on the nonradiative lifetime in GaAs/AlGaAs DHs of various thicknesses.

Including self-absorption and surface recombination, the effective minority carrier lifetime τ, is given by[7]

$$\frac{1}{\tau} = \frac{1}{\tau_r} - \frac{F}{\tau_r} + \frac{1}{\tau_{nr}} + \frac{2S}{d}$$

$$= \frac{1}{\phi\tau_r} + \frac{1}{\tau_{nr}} + \frac{2S}{d} \qquad (1)$$

where τ_r is the minority carrier radiative recombination lifetime, F is the fraction of photons from radiative recombination that are self-absorbed, $\phi = 1/(1-F)$, τ_{nr} is the nonradiative recombination lifetime, S is the interfacial recombination velocity, and d is the thickness of the GaAs layer. For injected minority carrier densities that are small compared to the carrier concentration, $p_0\ \tau_r = 1/(Bp0)$, where B is the radiative recombination constant.11 The factor ϕ in Eq. 1, which has been calculated for the GaAs/AlGaAs heterostructures,[7,10] depends on the sample's carrier concentration and thickness. ϕ increases as d becomes large compared to the absorption length of luminescence.

2. Experimental Technique

The recombination parameters, τ_r, τ_{nr}, and S can be determined from Eq. 1 using measurements of the effective minority carrier lifetimes on 3 GaAs/AlGaAs DHs with different GaAs thicknesses and the calculated[7,9] values for ϕ. The GaAs/AlGaAs DHs (Fig. 1) used to determine the recombination parameters consist of the following layers: a semi-insulating GaAs substrate, 500-Å p-$Al_{.5}Ga_{.5}As$, the p-GaAs active region, 500-Å p-$Al_{.5}Ga_{.5}As$, and a 50-Å p-GaAs cap layer. These DHs were grown without a distributed BR between the substrate and the DH. DHs with various

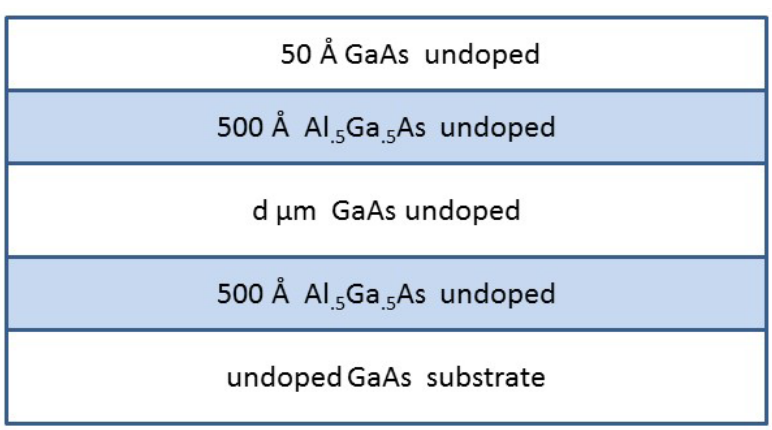

Fig. 1 GaAs/AlGaAs DH

GaAs layer widths (Fig. 2) were also grown with a distributed BR, comprising 10 periods of a 598-Å GaAs/726-Å $Al_{.8}Ga_{.2}As$ superlattice, between the substrate and the DH to study the effect of the BR on the nonradiative lifetime of the GaAs layer. The carrier concentration is the same in the GaAs and the AlGaAs regions. Carrier thickness and concentration were determined by MBE calibration procedures and electro-chemical capacitance-voltage measurements on calibration samples. Calculated values of the parameter ϕ as a function of d for $p_0 = 2.6 \times 10^{16}$ cm^{-3} and for $p_0 = 1.2 \times 10^{18}$ cm^{-3} have been published previously.[10,7]

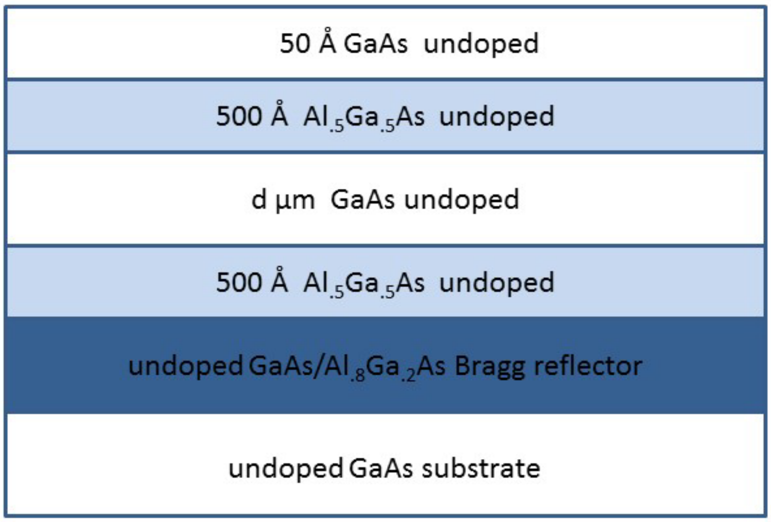

Fig. 2 GaAs/AlGaAs DH with a BR

TRPL measurements at 300 K were used to determine the PL decay time, which is the effective minority carrier lifetime. Samples were excited using a 250-kHz repetition rate, ultrafast 632-nm laser (~1.5-mm beam diameter) that was derived from frequency doubling the output of a regenerative amplifier-pumped optical parametric amplifier. PL was detected through a 700-nm long-pass filter to minimize the laser scattering signal, with a fast 300-μm diameter silicon (Si) photodiode. Data were acquired on a PCI averager card. The system response was measured to be ~2 ns.

3. Results

Figure 3 shows the observed TRPL data for a sample with d = 2 μm and $p_0 = 3 \times 10^{16}$ cm^{-3} for several excitation intensities. Figure 3 shows that above a certain excitation intensity, the PL spectra show a bimolecular and a nonexponential decay for the first 40 ns due to fast surface recombination as a result of screening of the electric field in the depletion region.[12] After the first 40 ns, or immediately after excitation at a low intensity, low-injection regime conditions

exist and a single exponential decay is observed. The effective minority carrier lifetime (the PL decay time) τ, is determined by fitting a single exponential decay to the low-injection tail of the PL decay. The PL decay is observed to be a single-mode exponential over roughly 2 decades with τ = 131 ns for excitation power ≤3.18 mW. For excitation power ≤3.18 mW, the estimated initial photoexcited carrier density is $\leq 6 \times 10^{14}$ cm^{-3} indicating that the excited samples are in the weak-injection regime.

Figure 3 shows that the PL decay cannot be fitted by a single-mode exponential for excitation power ≥12.4 mW, where the initial photoexcited carrier density is $\geq 3 \times 10^{15}$ cm^{-3} and the excited samples are entering the intermediate-injection regime. TRPL data for samples with $p_0 = 3 \times 10^{16}$ cm^{-3} and d = 0.6 and 0.3 µm, exhibit single-mode exponential decay over roughly 2 decades with τ = 82 ns and τ = 61 ns, respectively, for excitation power ≤1.13 mW. The observed structure in the PL intensity at times greater than 250 ns is more pronounced as τ decreases suggesting that it is an experimental artifact, which is related to the detector/circuit frequency response.

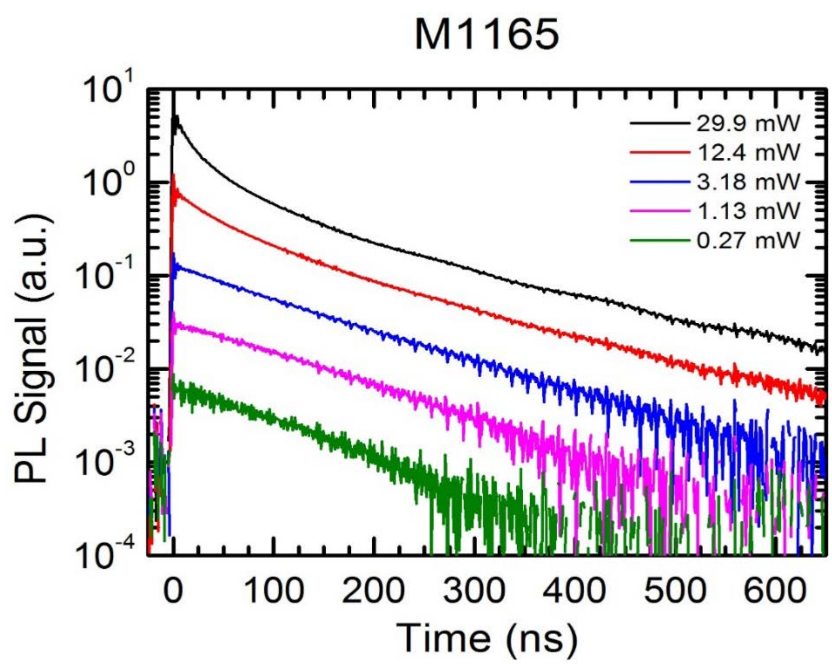

Fig. 3 TRPL data for a DH that was grown at 550 °C with an As/Ga flux ratio of 40

4. Data Analysis

The values for τ, d, and ϕ for the first 3 samples in Table 1, which do not have a BR, are substituted into Eq. 1 to determine τ_r, τ_{nr}, and S. The results obtained from the analysis show that for GaAs with carrier concentration of 3×10^{16} cm^{-3},

τ_r = 97.9 ns, τ_{nr} = 208.9 ns, and S = 74.8 cm/s. The low value of S obtained in our samples is comparable to the best values reported for MBE GaAs.[13] We also determine that the radiative recombination constant, $B = 1/\tau_r p_0 = 3.4 \times 10^{-10}$ cm^3/s, which is consistent with previous results.[10,14] The BR between the GaAs substrate and the DH is not expected to change the surface recombination velocity S, at the GaAs/AlGaAs interface[13] or the parameter ϕ for the DH with the 2-µm GaAs layer since all incident photons are absorbed before reaching the DH/BR interface at d = 2 µm.[7] Consequently, the recombination parameters derived from the TRPL lifetime measurements on the DHs without a BR can be used to determine the nonradiative lifetime of the DHs with a BR that are listed in Table 1, using Eq. 1.

Table 1 Sample data and PL decay times

Sample, MBE Parameters	p_0 (cm^{-3})	d (µm)	ϕ	τ(ns)	τ_{nr}(ns)
M1165, As/Ga =40, 550 C	3×10^{16}	2.0	4.83	131	209
M1167, As/Ga = 40, 550 C	3×10^{16}	0.6	2.07	82	209
M1166, As/Ga = 40, 550 C	3×10^{16}	0.3	1.54	61	209
M1285, As/Ga = 40, 550 C	3×10^{16}	1.0	3.0	101	209
M1288, As/Ga = 40, 550 C Bragg reflector	3×10^{16}	1.0	3.0	170	539
M1286, As/Ga = 40, 550 C Bragg reflector	3×10^{16}	2.0	4.83	212	539
M1278, As/Ga = 20, 595 C	1.6×10^{14}	20.0		871	932
M1284, As/Ga = 20, 595 C Bragg reflector	3.3×10^{14}	20.0		919	987

Previous studies (Fig. 4) have shown a significant increase in the nonradiative lifetime of MBE-grown GaAs/AlGaAs DH structures grown at 595 °C and an As/Ga flux ratio = 20 compared to DH structures that were grown at 550 °C and an As/Ga flux ratio = 40. This shows that DH structures that were grown using the non-optimal MBE parameters 550 °C and an As/Ga flux ratio = 40 have an increased deep level trap density.

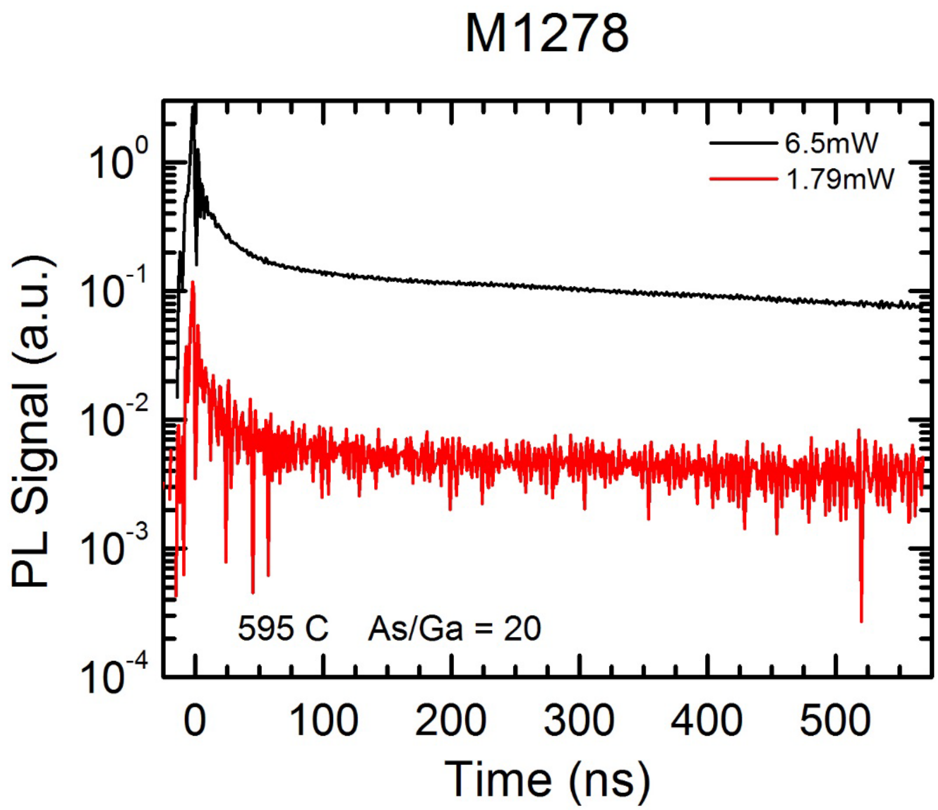

Fig. 4 TRPL data for a structure grown at 595 °C with an As/Ga ratio of 20

Table 1 shows that the growth of the BR in DH structures that were grown using non-optimal MBE parameters of 550 °C with an As/Ga flux ratio = 40, resulted in a large increase in τ_{nr} from 209 to 539 ns. In contrast, under optimized MBE growth conditions (595 °C with As/Ga = 20), the BR increases τ_{nr} from 932 to 987 ns.

5. Conclusion

In conclusion, a novel technique is used to determine the minority carrier lifetimes, the interface recombination velocity and the radiative recombination constant from time-resolved PL measurements on a set of 3 MBE-grown GaAs/AlGaAs DHs and published theory. This technique is used to determine that a distributed BR between the substrate and the DHs increases the GaAs nonradiative lifetime. The fractional increase in the nonradiative lifetime varies with the MBE growth parameters.

6. References

1. Kurtz SR, Faine P, Olson JM. J. Appl. Phys. 1990;68:1890.
2. Schnitzer I, Yablonovitch E, Caneau C, Gmitter TJ. Appl. Phys. Lett. 1993;62:131.
3. Keune DL, et al. J. Appl. Phys. 1971;42:2048.
4. Hwang CJ. Phys. Rev. B. 1972;6:1355.
5. van Opdorp C, Werkhoven C, Vink AT. Appl. Phys. Lett. 1977;30:40.
6. Dumke WP. Phys. Rev. 1957;105:139.
7. Asbeck P. J. Appl. Phys. 1977;48:820.
8. Panish HC, Jayson JS. J. Appl. Phys. 1971;42:2774.
9. Nelson RJ, Sobers RG. Appl. Phys. Lett. 1978;32:761.
10. Nelson RJ, Sobers RG. J. Appl. Phys. 1978;49:6103.
11. Sze SM. Physics of Semiconductor Devices. John Wiley & Sons, New York, 1981.
12. Rosenwaks Y, Thacker BR, Ahrenkiel RK, Nozik AJ. Phys. Rev. B. 1994;50:1746.
13. Dawson P, Woodbridge K. Appl. Phys. Lett. 1984;45:1227.
14. Casey HC, Stern F. J. Appl. Phys. 1976;47:631.

List of Symbols, Abbreviations, and Acronyms

As	arsenic
AlGaAs	aluminum/gallium arsenide
BR	Bragg reflector
DH	double heterostructure
Ga	gallium
GaAs	gallium arsenide
MBE	molecular beam epitaxy
PL	photoluminescence
S	surface recombination velocity
τ	effective minority carrier lifetime
τ_r	radiative lifetime
τ_{nr}	nonradiative lifetime
TRPL	time-resolved photoluminescence

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